

# Temporal and Spatial Development of TECs During Substorms

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and  
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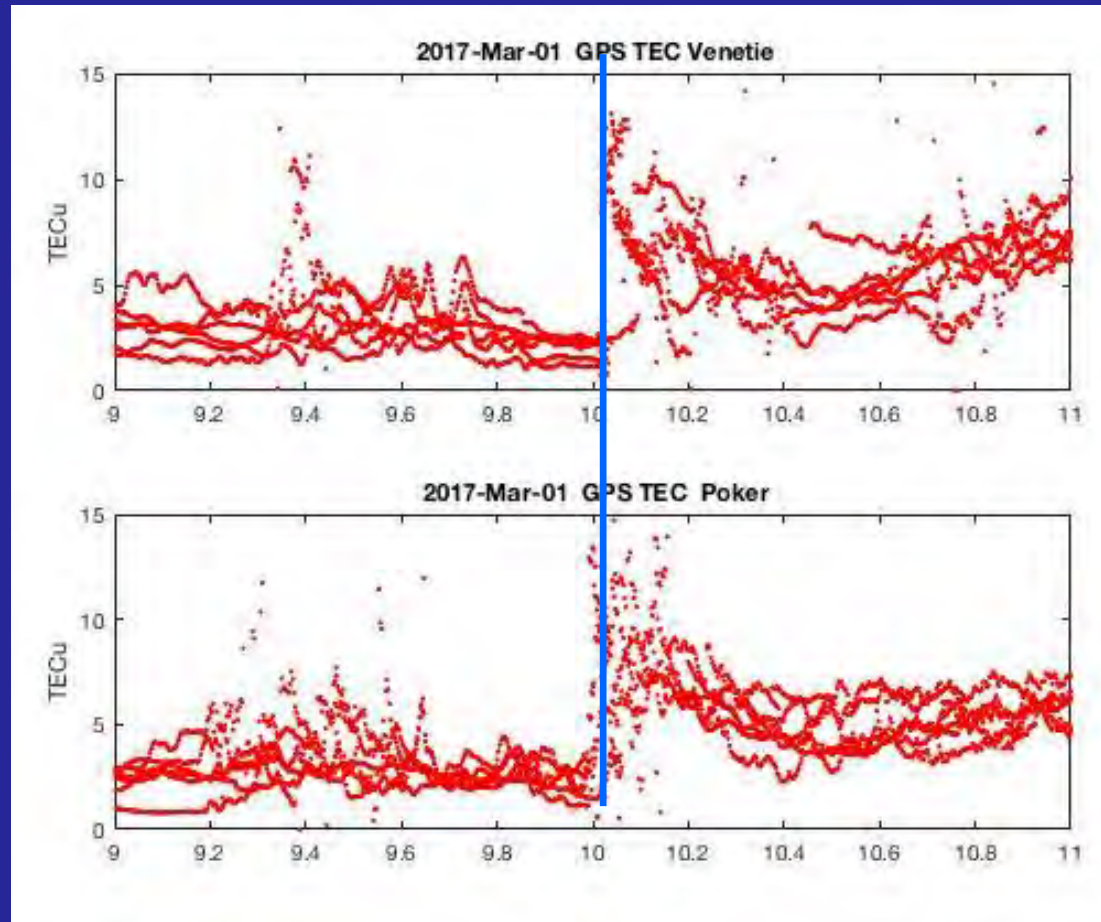
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Applied Physics Laboratory

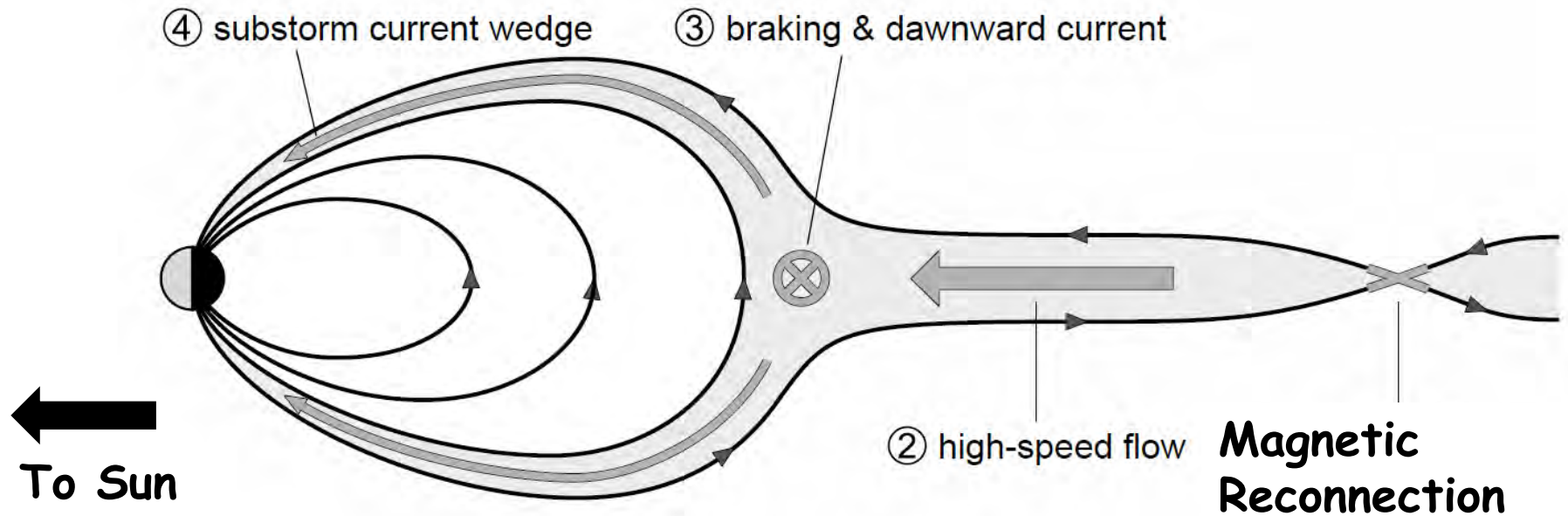


# Motivation

- Total Electron Content (TEC) enhancements can cause disruptions in communication and GPS systems.
  - The TEC is the *total* number of *electrons* present along a path between a radio transmitter and receiver. 1 TEC unit =  $10^{16}$  electrons/m<sup>2</sup>
- TEC enhancements can occur within the auroral oval during magnetic storms and substorms.
- It is not well known in which region of the auroral oval these enhancements occur and what is the source of these enhancements.
- We will use ionospheric currents derived from a large array of ground magnetometers to show TEC enhancements generally occur within the nightside region 1 current system.

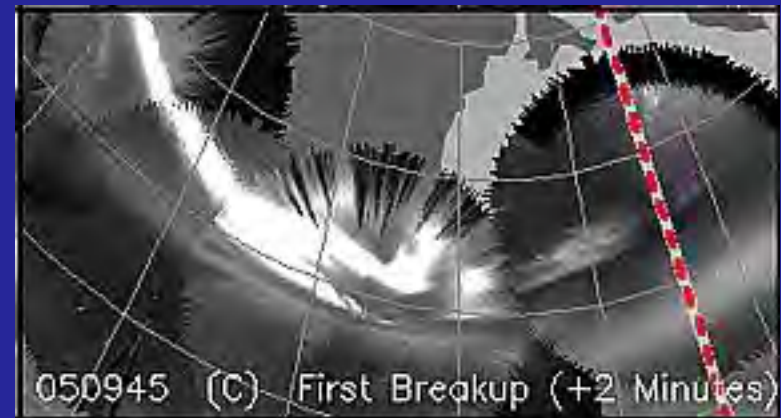


# Substorm Process within the Magnetotail



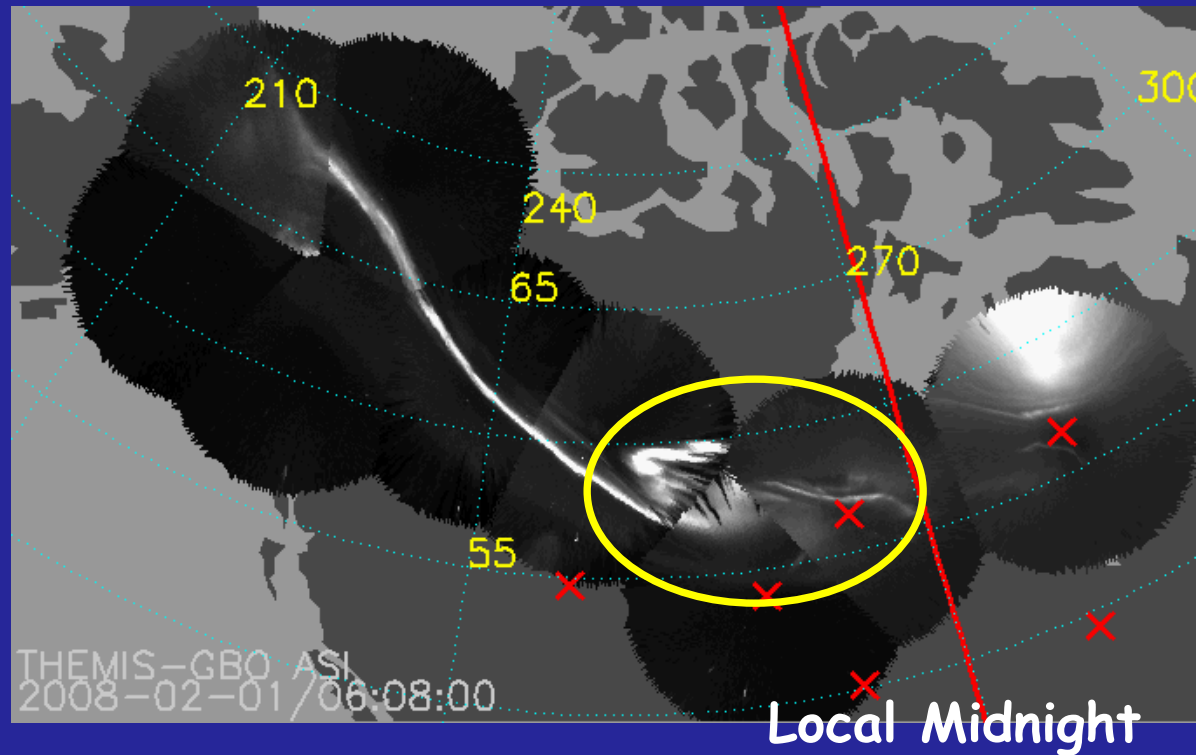
*Sequence of events during substorm onset (after Shiokawa et al., 1998).*

- Sequence of events during a substorm.
- Tail processes result in energized particle precipitation into the ionosphere.



# Data

- A subset of substorm onset times and locations (259 onsets) were determined from the THEMIS ASI images from the Chu and McPherron mid-latitude bay list.

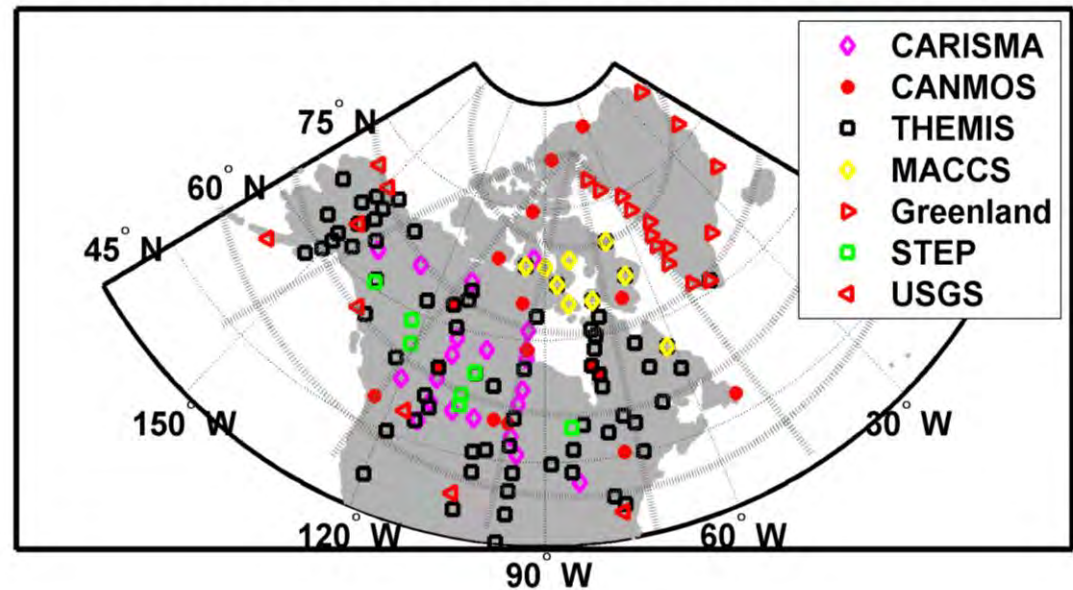


- Ionospheric current regions were derived using the spherical elementary current system (SECS) method.
  - Magnetometer data from 11 different ground magnetometer arrays.
- DMSP/SSJ precipitating electron and ion spectra and magnetometer data for spacecraft crossing from pre-noon to pre-midnight.
- vTEC data was obtained from the Madrigal online database at Haystack Observatory.

# North American Ground Magnetometers used to Derive Ionospheric Currents

- Inverted ground magnetometer fluctuations to get ionospheric currents.
  - *Amm and Viljanen [1999]*
  - *Weygand et al. [2011]*
- 11 Different ground arrays:
- AUTUMNX, CARISMA, CANMOS, DTU, Falcon, GIMA, MACCS, McMAC, STEP, THEMIS, & USGS.
- Potential for data from >150 stations.
  - Typically data from 60-90 stations per day.

CARISMA, CANMOS, GIMA, Greenland, MACCS, McMAC, THEMIS, STEP, USGS

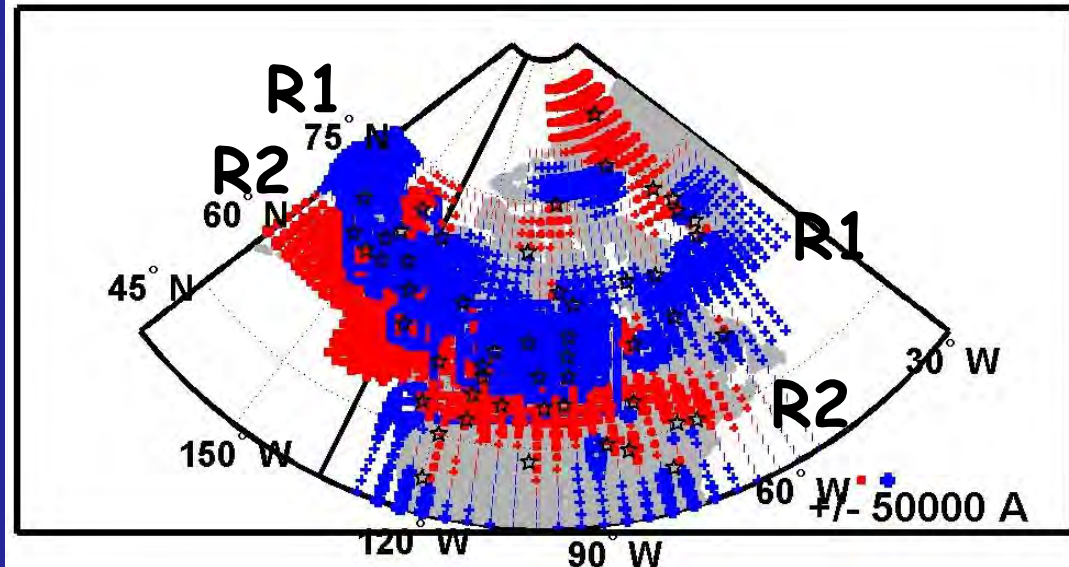
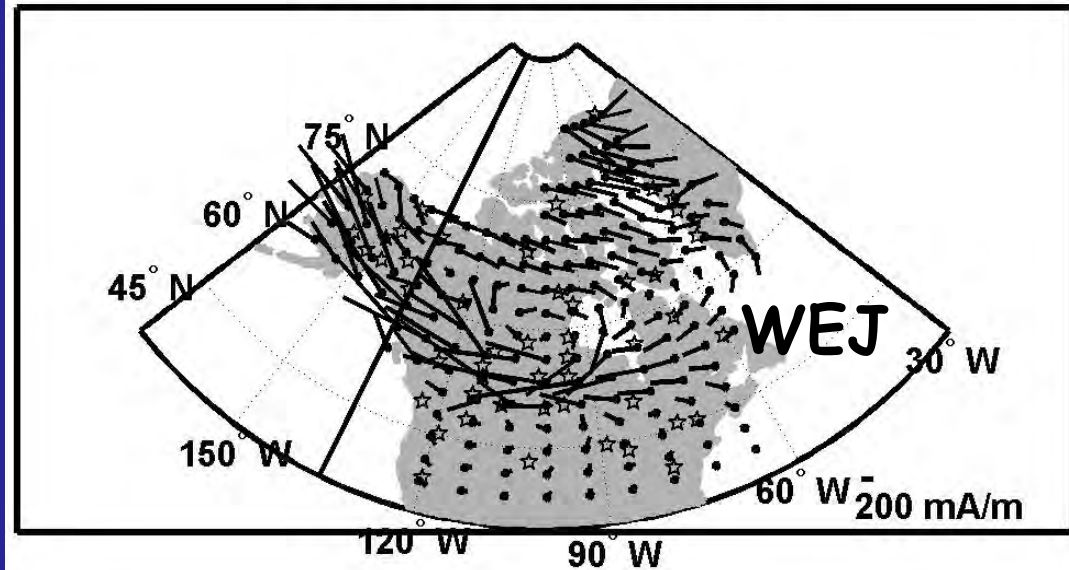


- Do not use data from Eastern Greenland or Iceland.
  - To far away.
- Current Amplitudes Resolution
  - $\Delta GLat$ :  $\sim 1.5^\circ$ ,  $\Delta GLon$ :  $\sim 3.5^\circ$ ,  $\Delta t$   $\sim 10s$
- Equivalent Ionospheric Currents
  - $\Delta GLat$ :  $\sim 3^\circ$ ,  $\Delta GLon$ :  $\sim 7^\circ$ ,  $\Delta t$   $\sim 10s$

# SECS Data Archive

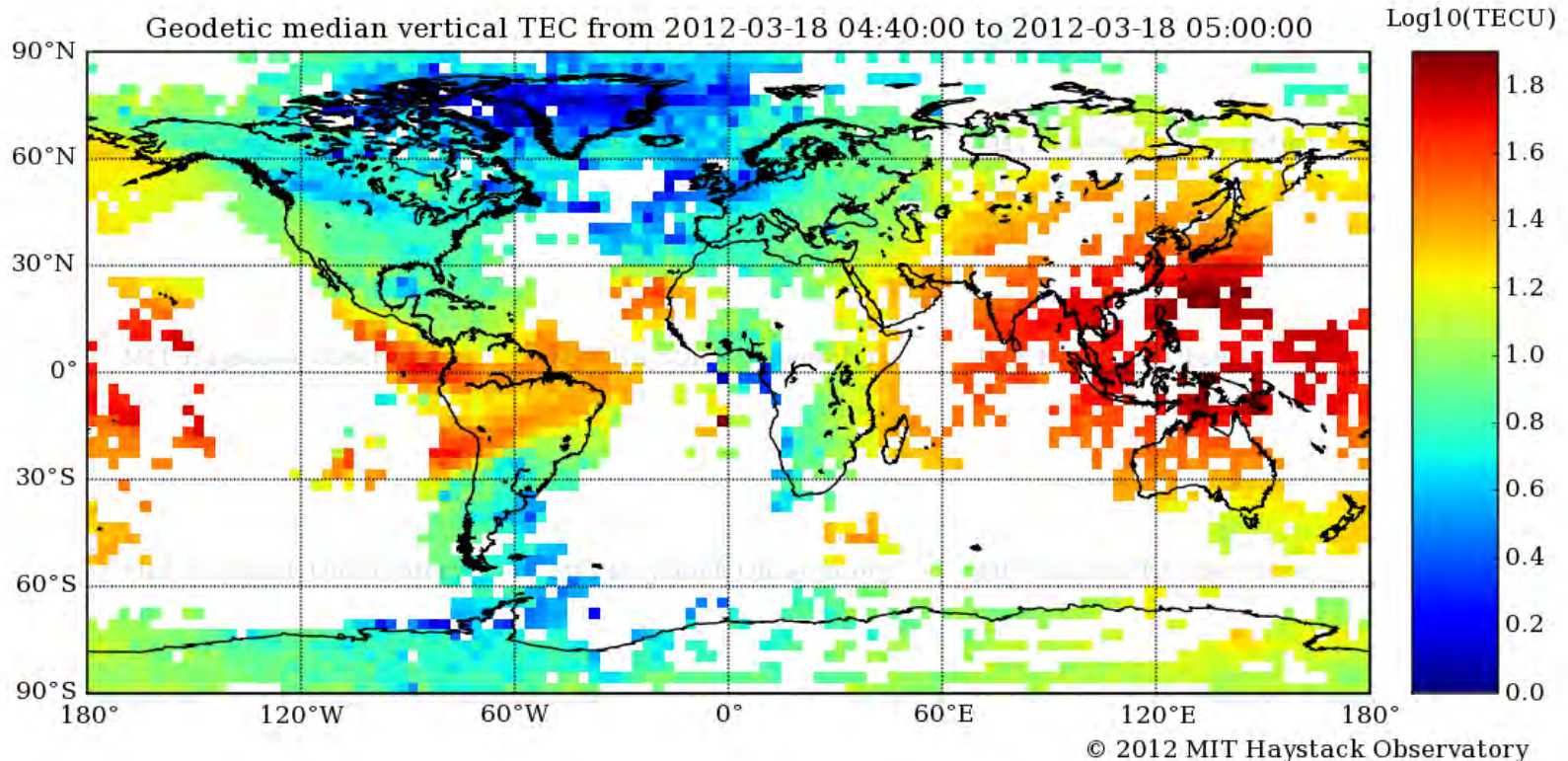
- Approximately 120 months of data online.
  - Between 2007 and 2019
  - Not complete.
  - Can calculate from any missing days between Jan 1, 2007 to Nov 30, 2019
- <http://vmo.igpp.ucla.edu>
- Backdoor:  
<http://vmo.igpp.ucla.edu/data1/SECS/>
- ASCII data files 10 s res.
- Quicklook plots (Example plot)
  - Top: Equivalent ionospheric currents
  - Bottom: Current Amplitudes

SECS: 05-Apr-2010 09:00:00

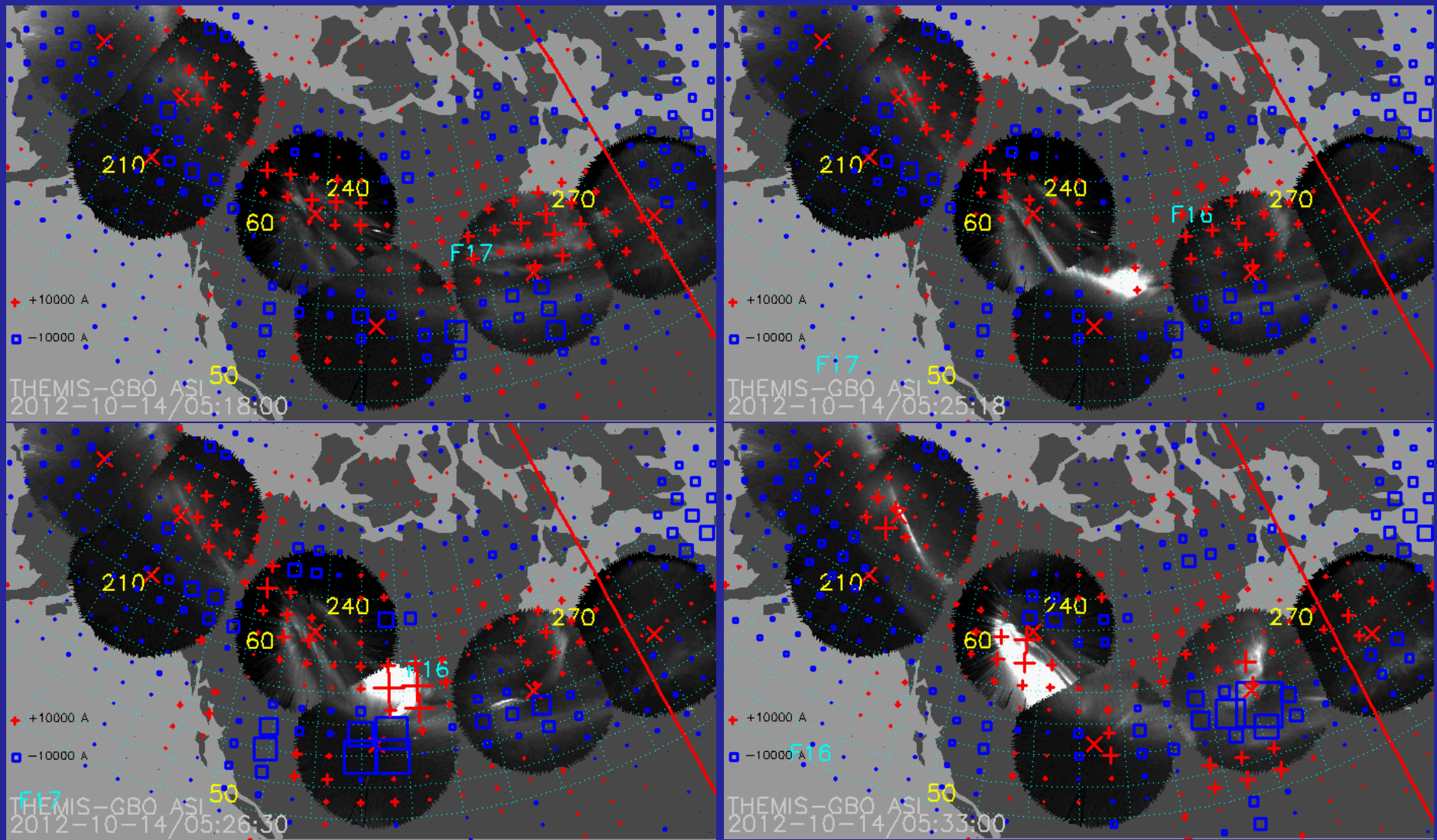


# Slant TEC and Vertical TEC

- Propagation of radio waves is affected by the electrons in the ionosphere.
- The velocity of radio waves changes when the signal passes through the ionosphere.
- The total delay of the waves depends on the frequency of the radio wave (known), the electron density profile, and the slant TEC values between the transmitter and the receiver.
- Vertical TEC derived from slant TEC using the elevation angle of the transmitter.



# Substorm Onset: 2012/10/14 ~0525 UT

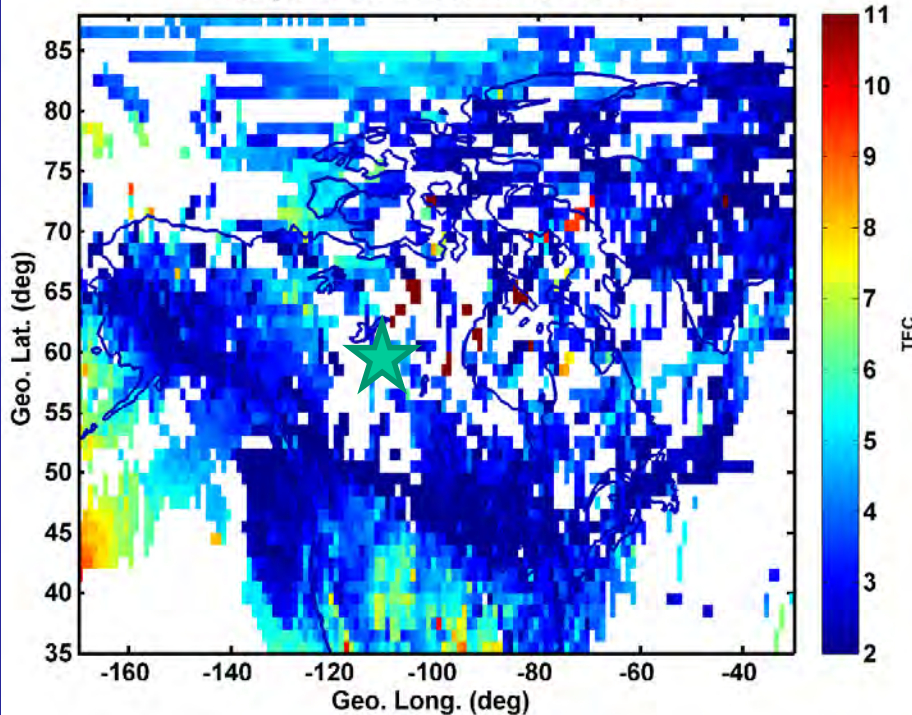


- DMSP 16 & 17 mapped from the southern hemisphere.
- Blue □: downward current. Red +: upward current.

# Northern Hemisphere vTECs: 2012/10/14

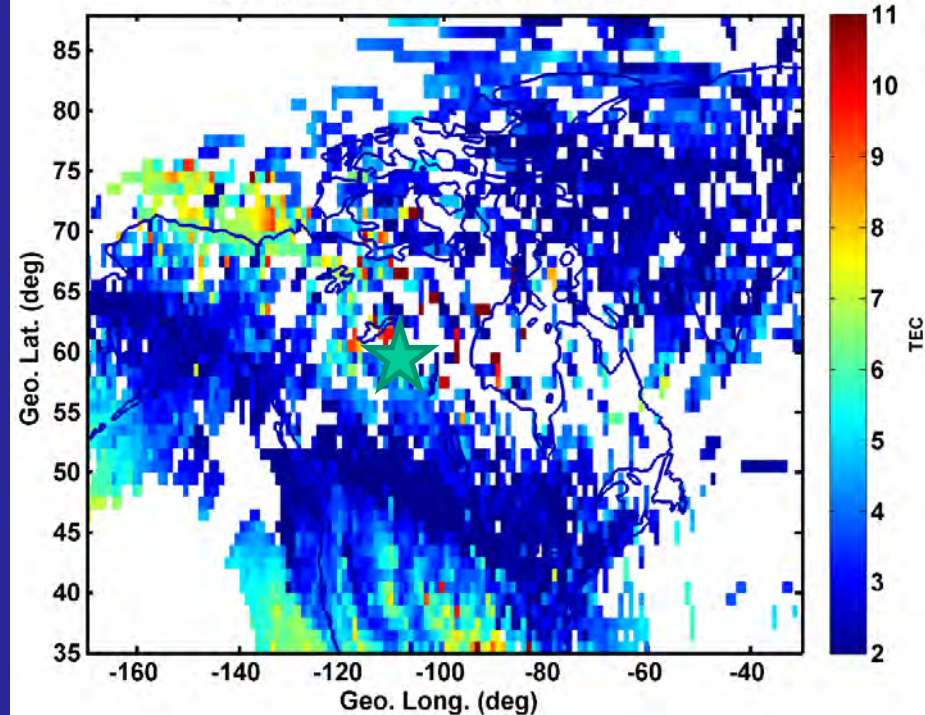
Before Onset

Madrigal TECs: 14-Oct-2012 05:05:00



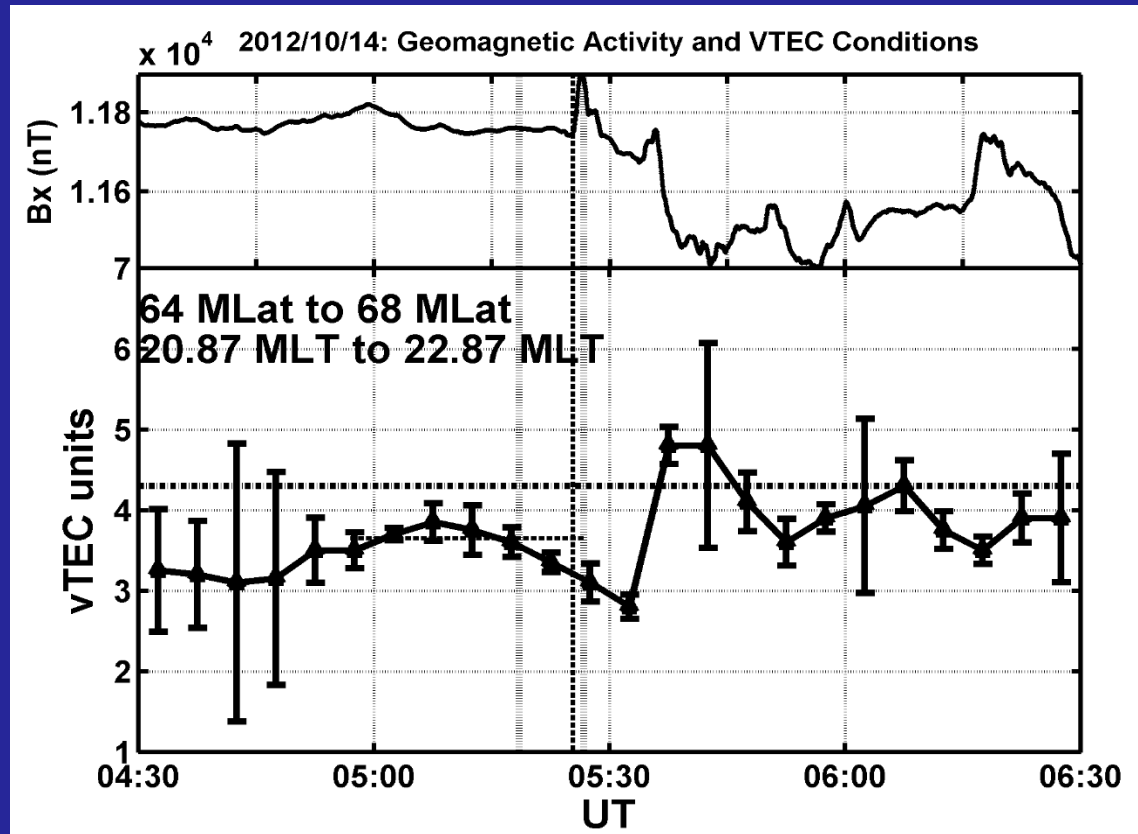
After Onset

Madrigal TECs: 14-Oct-2012 05:35:00



- vTEC values over North America and Greenland
- Green star marks the onset location.

# Correlation between Ground Magnetometer Bx Data and vTEC data



- Times series of median vTEC values derived from auroral region.
- Black vertical line marks onset time.

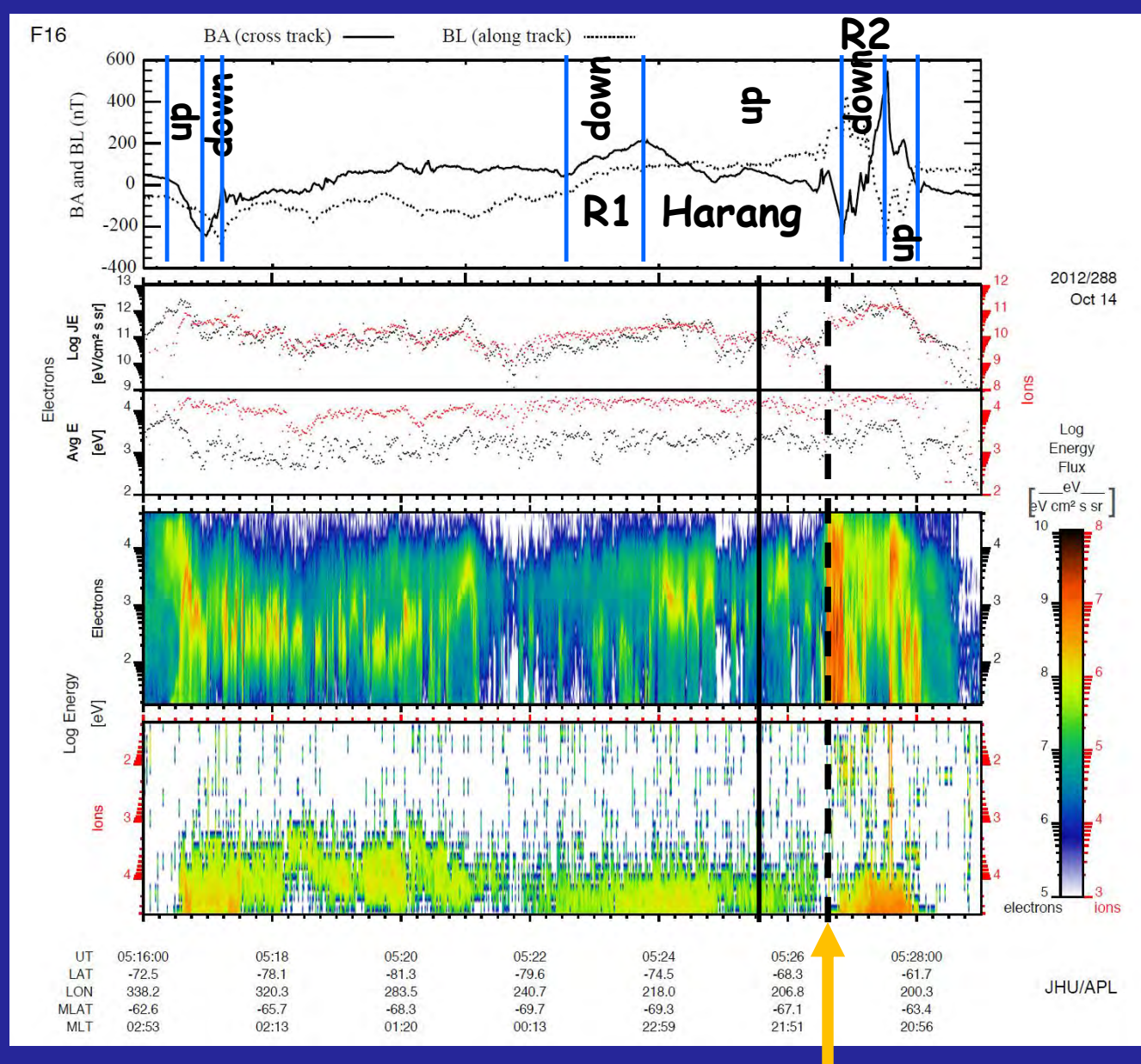
- Data from approximately the same time.

- Blue lines: marked current region boundaries.



# DMSP Magnetic field and Particle Spectra After Enhancement

- Data from approximately the same time.
- Black solid line marks the time of the auroral onset.
- Black dashed line marks the point when DMSP is within the vicinity of the aurora onset location.
- Blue lines: marked current region boundaries.

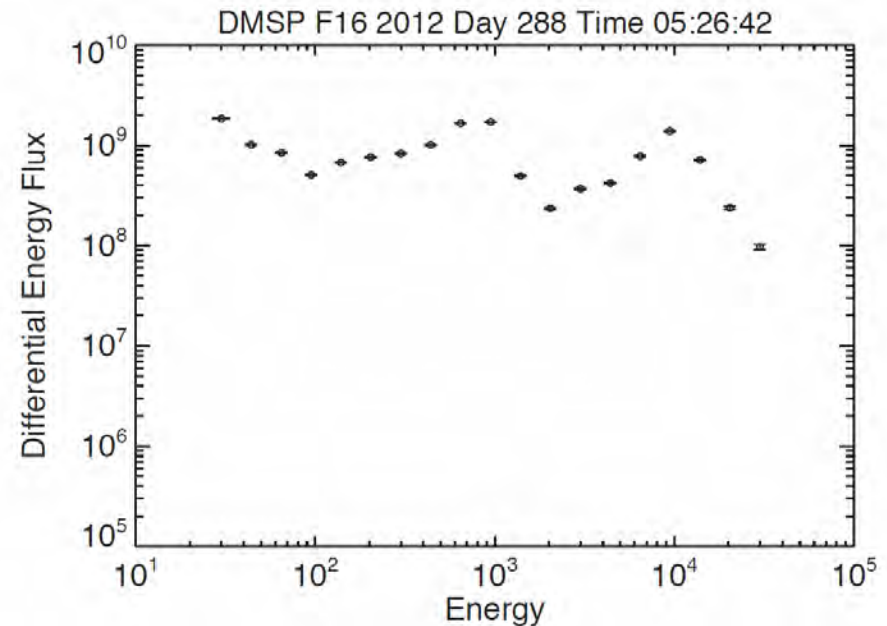
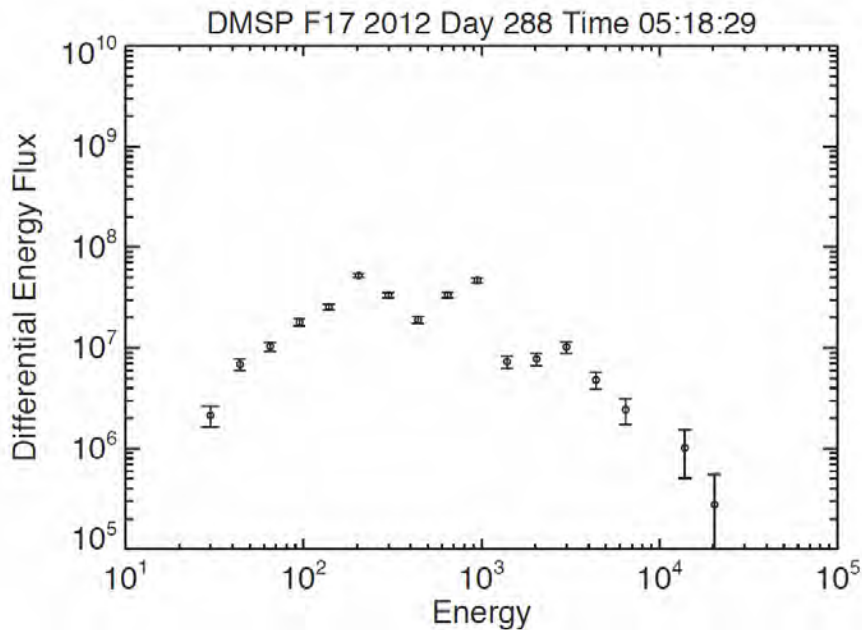


Electron precipitation enhancement.

# Electron Flux Enhancement in Harang Upward Current

Mat:  $-65.7^\circ$ , MLT: 21:42

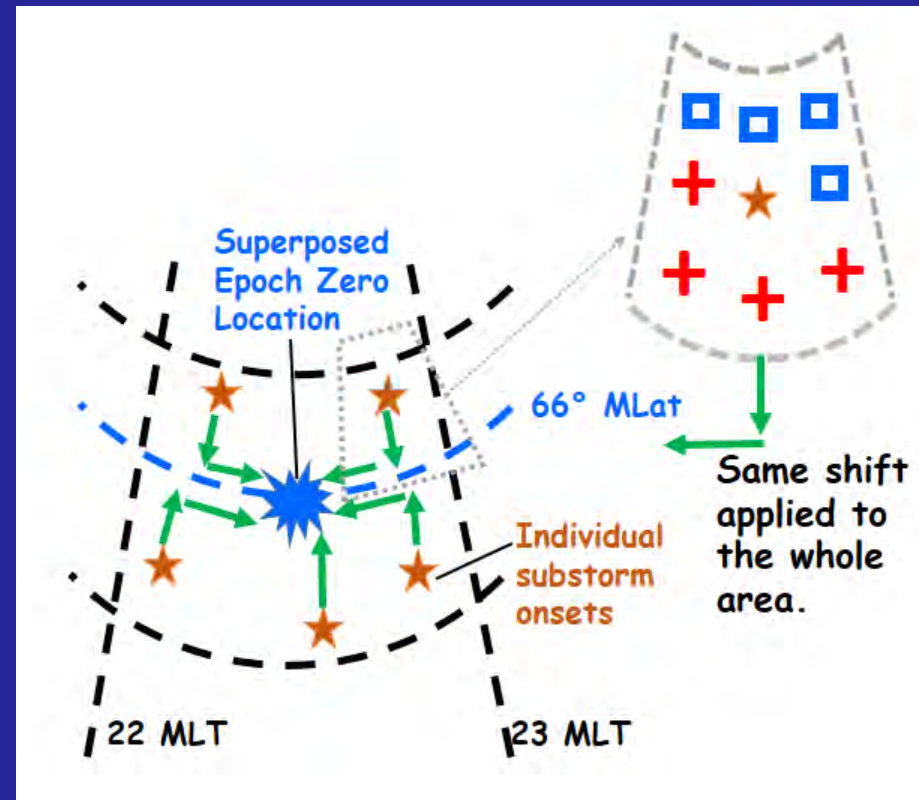
Mat  $-65.9^\circ$ , MLT: 21:30



- F17: broadband electrons at 05:18:29 UT.
- F16: monoenergetic and broadband electrons at 05:26:42 UT.
- Increase of  $\sim 100$  in Harang upward current.
- Increase of  $\sim 8$  in R1 downward current (not shown).

# Superposed Epoch with 2D Array of Currents and TECs Shows Average Development of Substorms

- Shift auroral onset location to 66 Mlat & 22.5 MLT [Frey et al., 2004].
  - Approximate average location of auroral substorms from IMAGE auroral images.
  - Used 48 onsets within 0.5 hr of 22.5 MLT.
  - Included moderate to large substorms ( $AL < -350$  nT).
  - Shifted currents and TECs of earlier and later times in same manner.
- vTECs from Madrigal database.

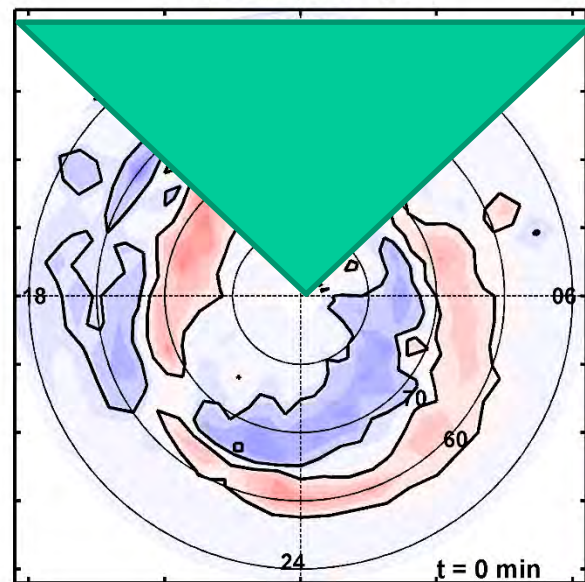
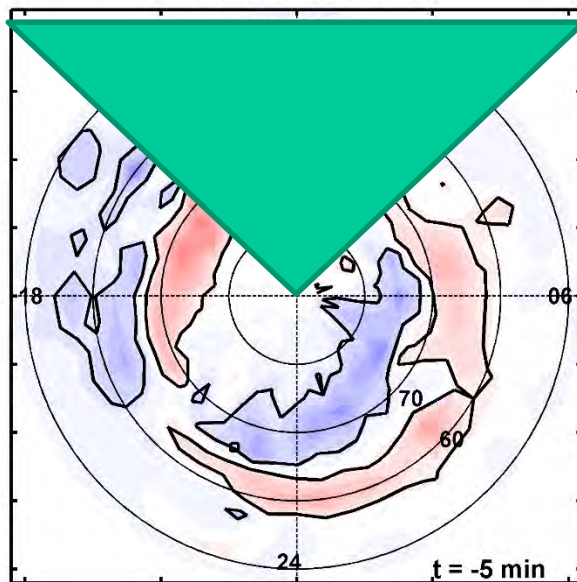
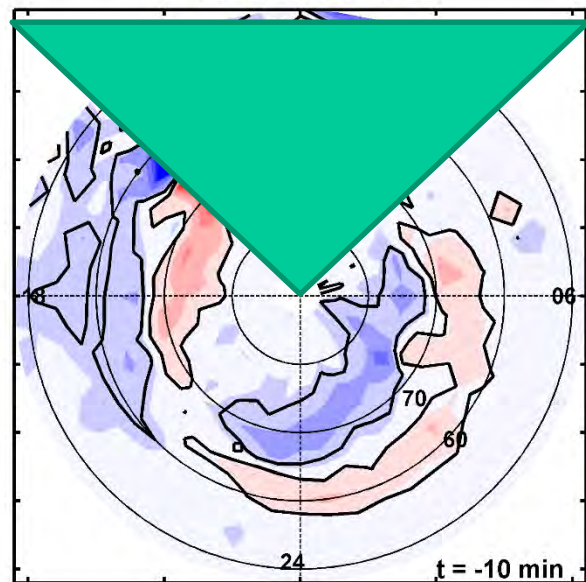


# 2D Superposed Epoch: Current Enhancement

SECS Superposed Epoch

SECS Superposed Epoch

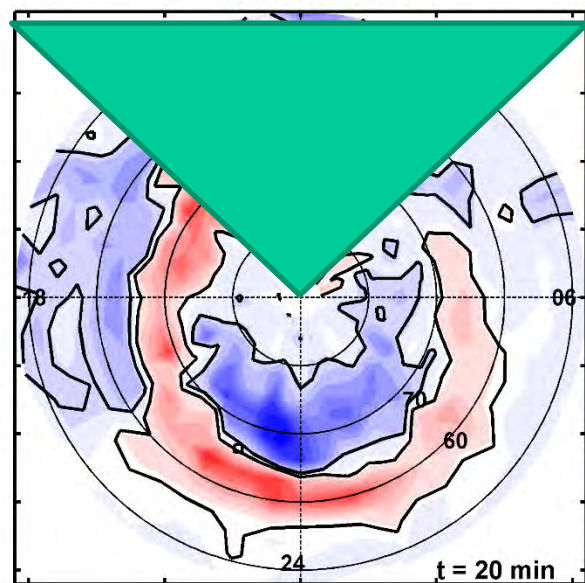
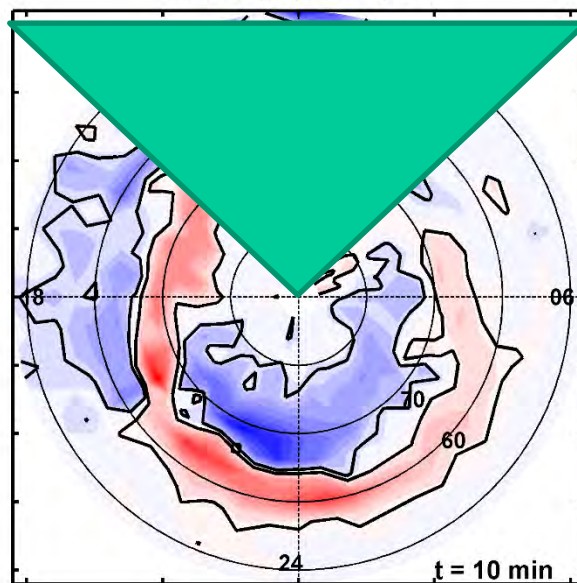
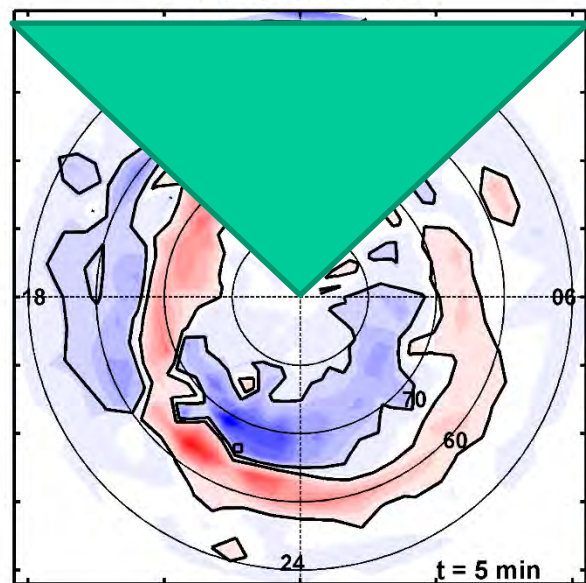
SECS Superposed Epoch



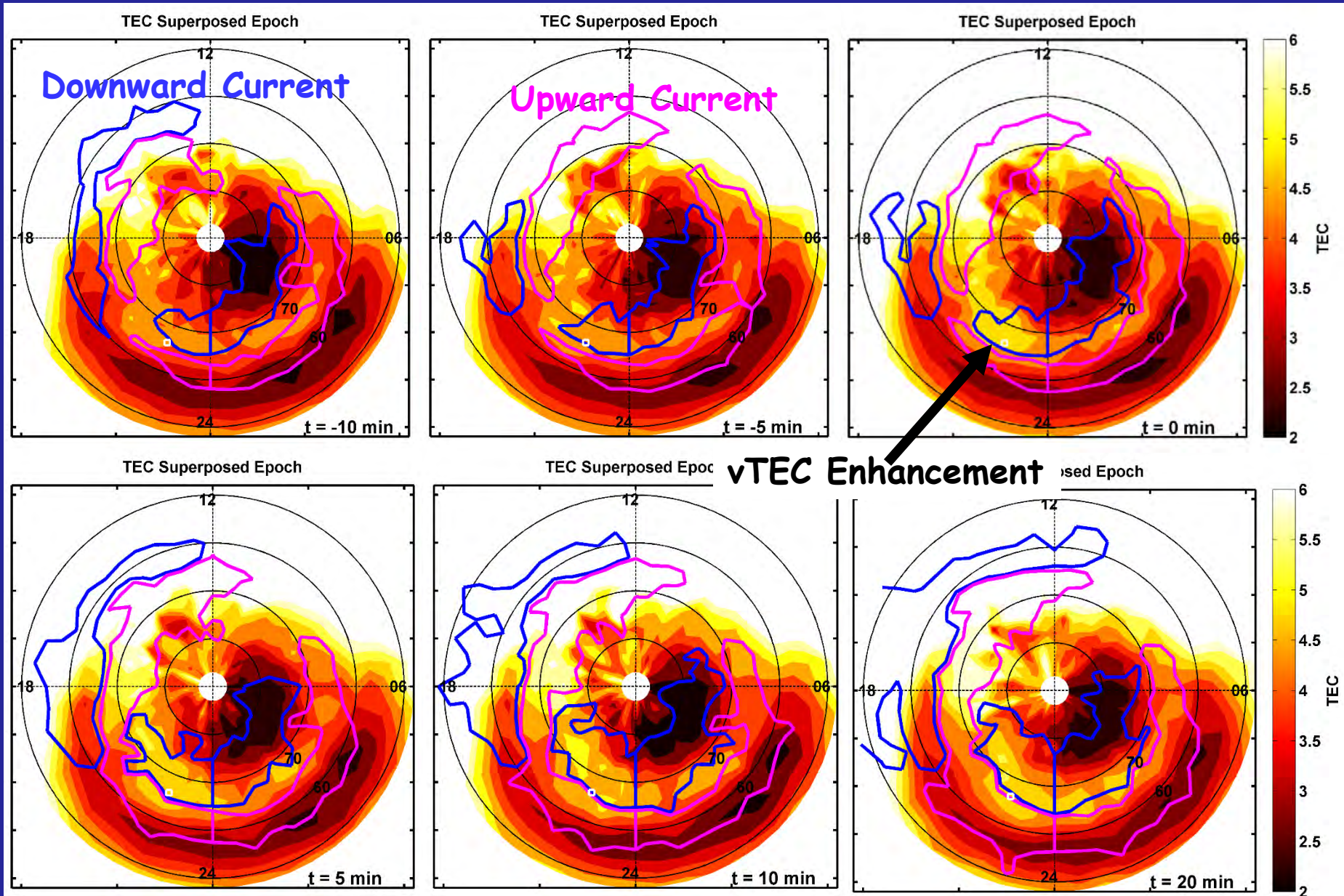
SECS Superposed Epoch

SECS Superposed Epoch

SECS Superposed Epoch

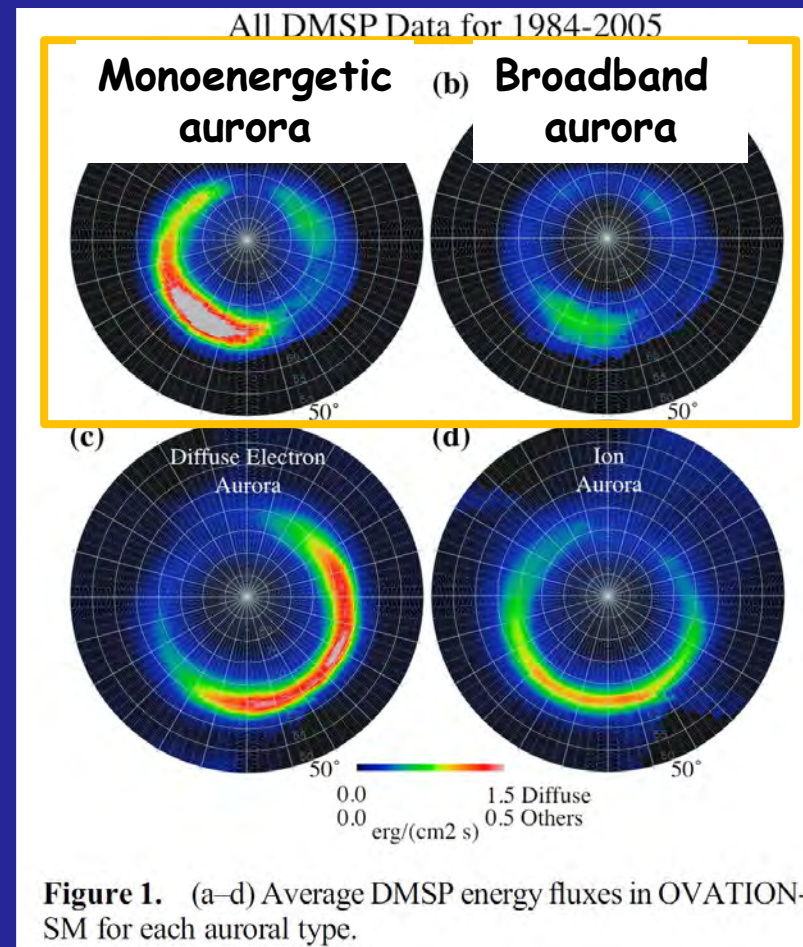


# 2D Superposed Epoch: TEC Enhancement



# Discussion and Conclusion

- Superposed epoch together both moderate & strong substorms.
  - Peak enhancement of TECs within first 10 min of substorm onset.
  - Enhancement occurs mainly in the region 1 downward currents.
  - Enhancements lasts ~40 min.
- What is the mechanism for enhancement?
  - Enhanced plasma sheet electron precipitation?
    - ~factor of 10 to 100
  - Distribution of TEC enhancement **similar** to OVATION-SM distribution for monoenergetic aurora.



Mitchell et al. [2013]

# Magnetometer Acknowledgements

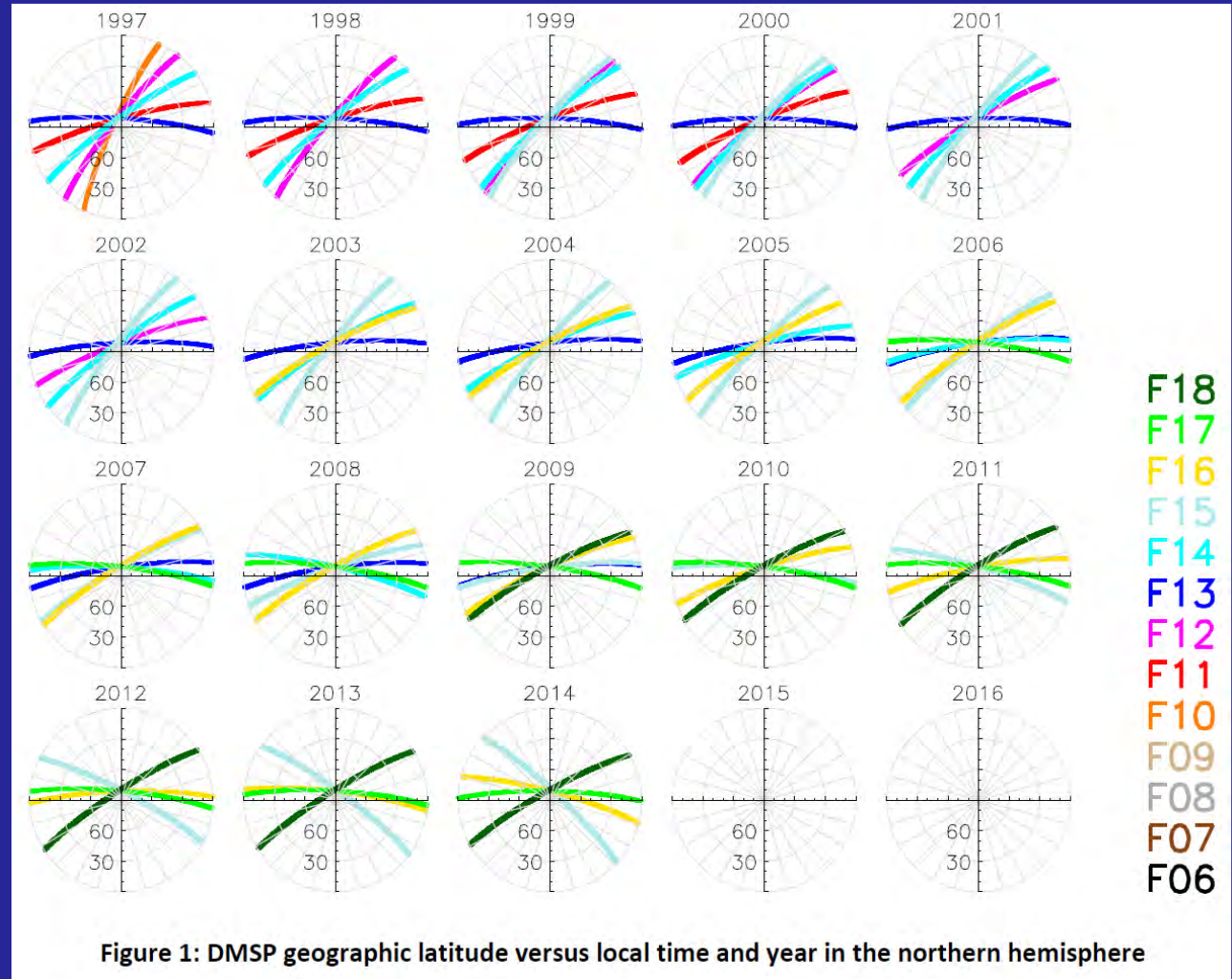
- **AUTUMNX:** This magnetometer network is funded through the Canadian Space Agency(CSA) / Geospace Observatory (GO) Canada program
- **CARISMA and CANMOS:** These data were obtained from the Canadian Space Science Data Portal. The Canadian Space Science Data Portal is funded in part by the CSA, the Alberta Science and Research Authority (ASRA), and the University of Alberta (UofA). CANMOS data were obtained by the Canadian Magnetic Observatory Network (CANMON), maintained and operated by the Geological Survey of Canada, provided the data used in this study.
- **DMI:** The Danish Meteorological Institute (DMI).
- **Falcon:** United States Air Force Academy (USAFA) and Peter Chi.
- **GIMA:** Geophysical Institute, University of Alaska Fairbanks.
- **MACCS:** Magnetometer Array for Cusp and Cleft Studies array is supported by US National Science Foundation grant ATM 0827903 to Augsburg College. We would like to would like to thank the following: M. J. Engebretson, D. Murr, and E.S. Steinmetz at Augsburg College and the MACCS team.
- **McMAC:** Project is sponsored by the Magnetospheric Physics Program of National Science Foundation and maintained by Dr. Peter Chi.
- **THEMIS:** We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission, S. Mende and C. T. Russell for use of the GMAG data, I. Mann for use of the GMAG data, and the CSA for support of the CARISMA network.
- **STEP:** Magnetometer file storage is at Department of Earth and Planetary Physics, The University of Tokyo and maintained by Dr. K. Hayashi.
- **USGS:** The USGS Geomagnetism Program



EXTRA SLIDES AFTER THIS SLIDE

# Defense Meteorological Satellite Program Spacecraft

- Began in the 60s.
- In LEO orbit at ~850 km.
- In the 80s magnetic field and particle instruments added and data made available.
- Fluxgate magnetometer (SSM) provides 1 s resolution data.
- Electron/Proton spectrometer measures precipitating electrons and ions at 1 s resolution.

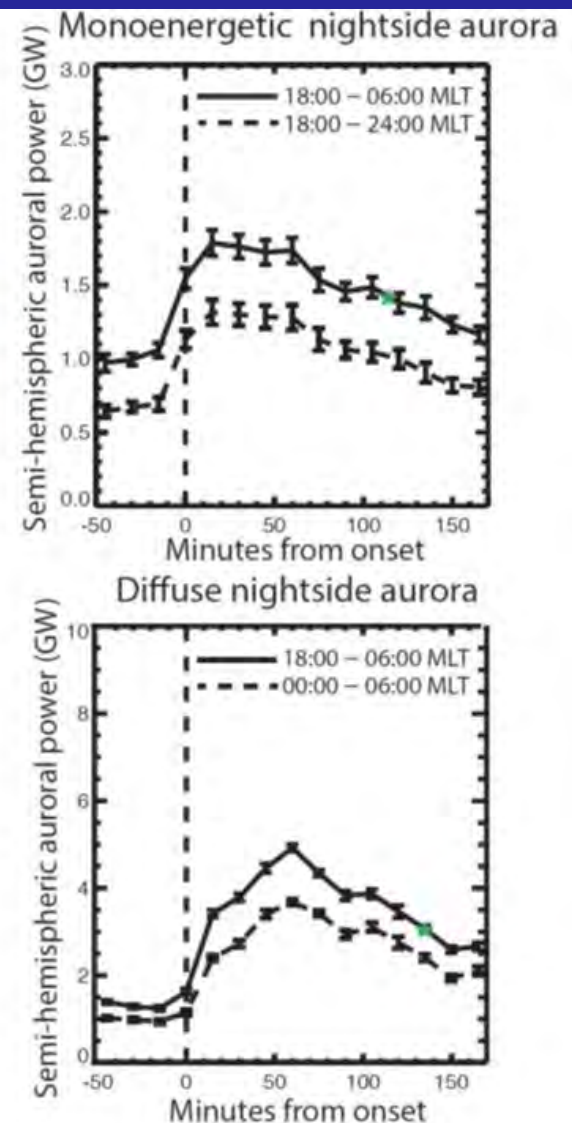
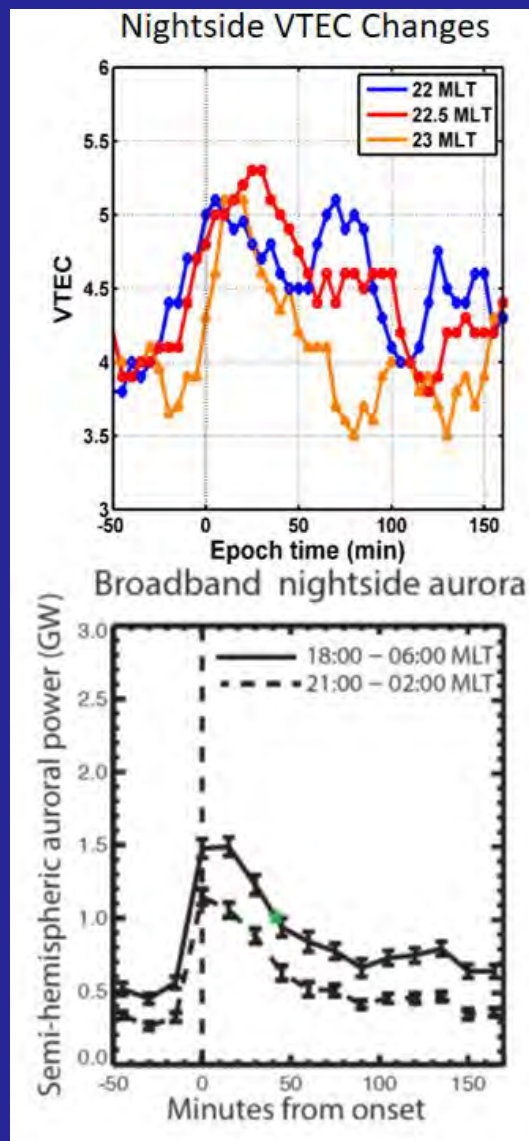


Ober [2014]

- DMSP cross the auroral region:
- dawn to dusk meridian or
- pre-noon to pre-midnight meridian

# 1D Superposed epoch comparison with Wing et al. [2013]

- Upper left: vTEC vs. epoch time for three MLTs.
- Upper right: auroral power associated with monoenergetic electron precipitation.
- Lower left : auroral power associated with broadband electron precipitation.
- Lower right: auroral power associated with electron precipitation within the diffuse aurora.



# Substorm Process within the auroral oval Akasofu [1964]

- Classic aurora sub storm picture.
- T= 0-5 min: FACs and electrojet currents intensify.
- T=5-10 min: currents reach maximum intensity.
  - Aurora expands poleward, westward, and eastward.
- Currents/Aurora mostly recover by about 1 to 2 hr later.

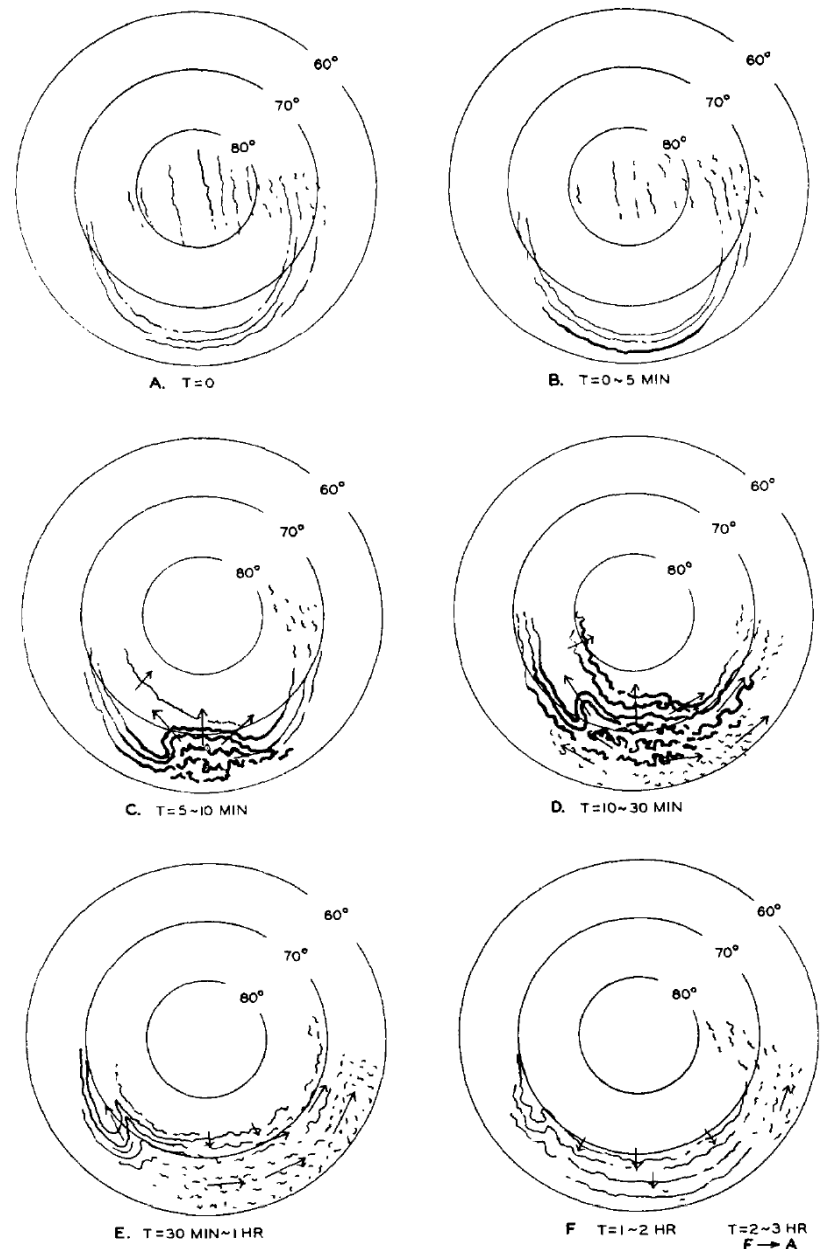


FIG. 1. SCHEMATIC DIAGRAM TO ILLUSTRATE THE DEVELOPMENT OF THE AURORAL SUBSTORM. THE CENTER OF THE CONCENTRIC CIRCLES IN EACH STAGE IS THE NORTH GEOMAGNETIC POLE, AND THE SUN IS TOWARD THE TOP OF THE DIAGRAM.

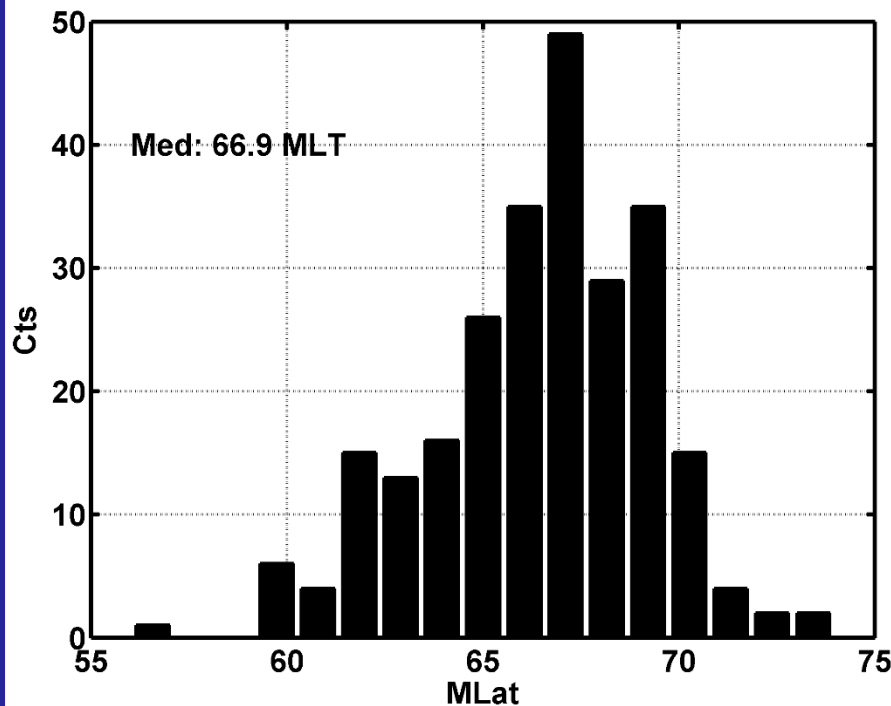
# Statistics (1 of 2)

- 259 auroral onsets in the northern hemisphere with mid-latitude bays.
  - All have vTEC data and ionospheric currents.
- 148 events with potential DMSP data:
  - DMSP foot point crosses within 1 hr of local time of the onset.
    - All DMSP in southern hemisphere during onset.
  - About 15 minute before or after the onset.
- 102 of the 148 show some TEC enhancement within the vicinity of the onset.
  - ~69 %
  - 69 events DMSP crosses before onset.
  - 68 events DMSP crosses after onset.
- 3 events with 2 separate DMSP crossing before and after the onset.

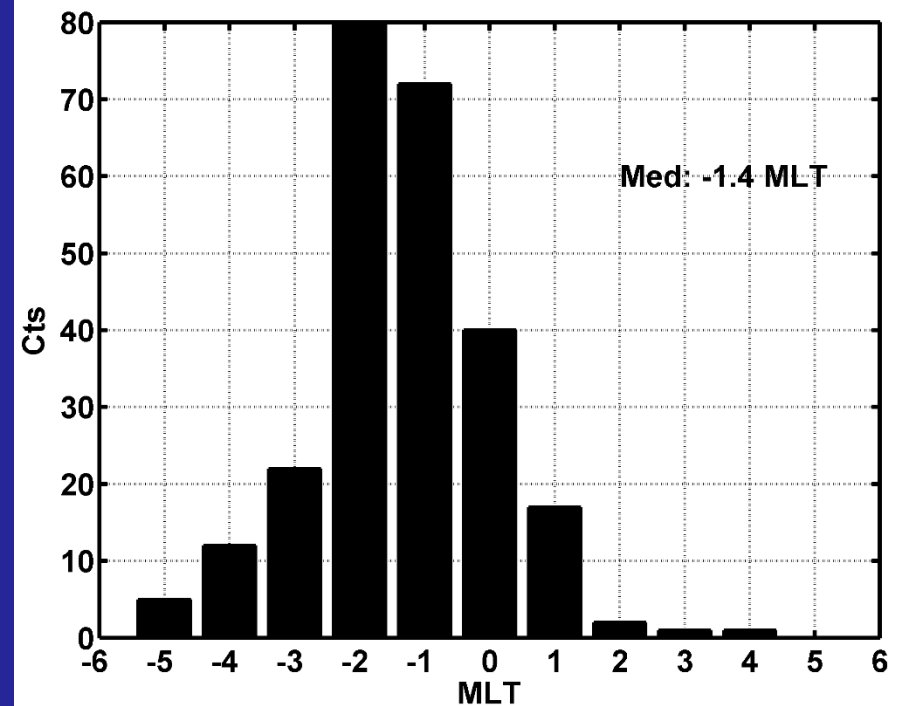
# Superposed Epoch with 2D Array of Currents and dB/dt

- Identify auroral substorm onset in auroral images.
  - Substorms from Chu and Mcpherron mid-latitude bay list.
    - Total of 1624 mid-latitude bays.
    - Identified 263 with auroral onsets.
  - Similar to 66 Mlat & -1 MLT with IMAGE s/c [Frey et al., 2004].

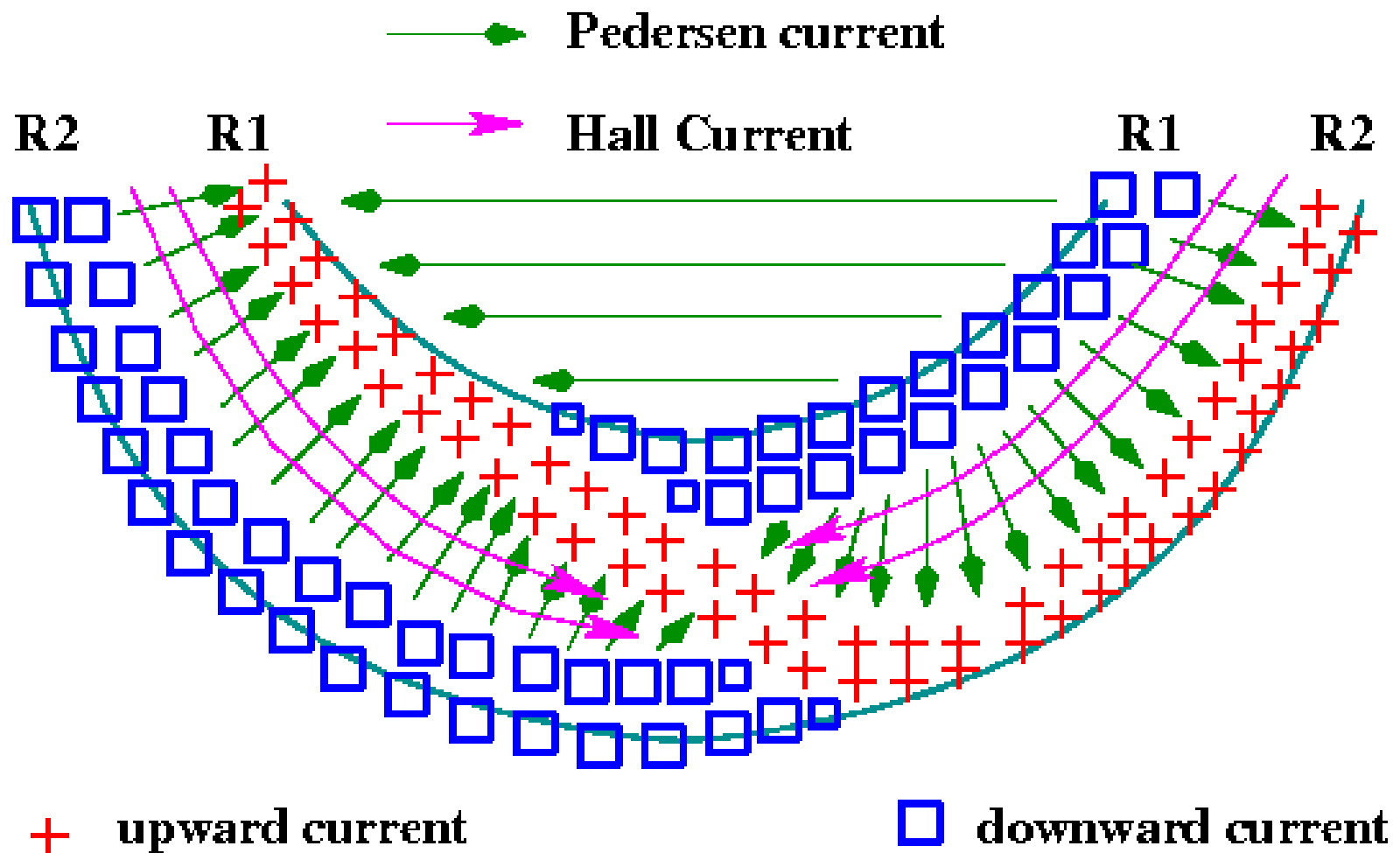
MLat distribution of Auroral Onsets



MLT distribution of Auroral Onsets



# Nightside Ionospheric Current System



**Fin**